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Life Cycle Assessment of a Diesel Engine Based on an Integrated Hybrid Inventory Analysis Model

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Abstract

This paper conducts a Life Cycle Assessment (LCA) to evaluate the energy consumptions and environmental emissions of an engine with Integrated Hybrid Life Cycle Inventory (IH-LCI) analysis method. Aggregated Input–Output matrix A_{int} is established by the methods of site investigation, data collection, and input-output analysis. Furthermore, the paper compares the results of this study with the one achieved by the process based inventory analysis method to show the sources of the differences between the two methods. Data quality of both the methods is checked by uncertainty analysis. The result can be used for exploring the optimal boundary division by LCA practitioners when applying the IH-LCI for more convenient and accurate decision making in future.

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Keywords: Hybrid inventory analysis; Diesel engine; Economic Input-Output LCA; Uncertainty analysis

1. Introduction

1.1. Background

China has become a giant centre of internal combustion engine manufacturing. In 2012, the total value of engine output has reached 370 billion Yuan, total power exceeded 1.5 billion kW, and social ownership broke through 300 million sets [1]. The rapid development of the internal combustion engine industry has brought about serious resource and environmental problems. In 2011, the oil consumptions of the Chinese internal combustion engine industry accounted for 60% of the country's oil use, and the internal combustion engine industry exhaust gas pollution is one of the main urban atmospheric pollution sources, accounting for more than 50% of the atmospheric pollution in the vast majority of the cities in China during the no-heating season [2]. The environmental-friendly and sustainable development of the internal combustion engine industry has attracted more and more attention. The government has

formulated series of energy conservation and pollutants reduction policies for combustion engine.

As a useful and systematic tool to analyze and manage the environmental impacts over the entire life cycle of product, Life Cycle Assessment (LCA) has been applied intensively and has received great attention from industry and academia. Life cycle inventory (LCI) analysis is the foremost constituent of LCA, in which the data are collected and organized. LCI is the basis to evaluate comparative environmental impacts or potential improvements. Data missing has become the chief obstacle of LCI compiling, and the level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process [3].

Nowadays, there are mainly six kinds of LCI analysis methods, subdivided in following three categories: process based life cycle inventory (P-LCI)-process flow diagram and matrix representation; economic input-output based life cycle inventory analysis (EIO-LCI); hybrid life cycle inventory analysis-tiered hybrid analysis, IO-based hybrid analysis and integrated hybrid analysis [4]. The mutual comparisons of the

six methods, including data requirements, data uncertainty, upstream system boundary, applicable analytical tools, etc., have been discussed in reference [4]. The framework for LCI methods is shown in Fig. 1.

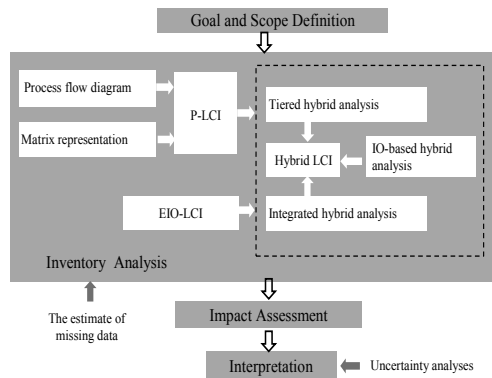


Fig. 1. The framework for LCI methods

1.2. Research objective

P-LCI for an engine is highly time and labour intensive due to the complexity of the engine's structural system. This paper conducts an LCA to evaluate the energy consumptions and environmental emissions of an engine with an integrated hybrid life cycle inventory (IH-LCI) analysis method. Furthermore, the result of this study is compared with that of P-LCI method to show their gaps and better understand the sources of their differences. The result can be used to explore the more convenient and accurate decision making in future for LCA practitioners.

2. Methodology Theoretical Analyses

Currently P-LCI and EIO-LCI are the two fundamental LCI models. P-LCI is a conventional method which entirely relies on a bottom-up construction approach of the supply chain based on facility level data regarding material and energy flows. EIO-LCI inherently covers infinite orders of upstream production stages and provides a flexible tool for comprehensive LCA of products. EIO-LCI is a top-down approach in which the statistical data on production and consumption in individual industrial sector allows a complete allocation of all the activities to all the products. Advantages and limitations of P-LCI and EIO-LCI are shown in Table 1.

2.1. EIO-LCI

Combining life cycle assessment and economic input-output is based on the work of Leontief in the 1930s. Leontief developed the idea of input-output model of the U.S. economy and theorized about expanding them with non-economic data [5]. The total amount of industry output X required by an arbitrary final demand for industry output F is calculated by Eq. (1). [6]

Table 1. Advantages and Limitations of P-LCA and EIO-LCA

	P-LCI	EIO-LCI
Advantage	1. High data reliability	1. complete system boundary
	2. Specific and detailed data sources	2. Convenient data collection
	3. low uncertainty	3. low time and labour intensity
Limitation	1. Incomplete system boundary	1. Macroscopically data sources,
	2. Heavy data collection work	2. Complex data analysis work
	3. high time and labour intensity	3. Exclude usage and disposal phrase

$$X = (I - A)^{-1} F \quad (1)$$

Where, matrix A represents the direct requirements of the intersectoral relationships in input-output tables (IOT). The rows of A indicate the amount of output from industry i required to produce one dollar of output from industry j ; I represents the $n \times n$ identity matrix.

Hendrickson et al proposed the EIO-LCA based on EIO table and environmental intervention coefficient R [7]. The amount of industry-wide environmental intervention E generated by an arbitrary final demand for industry output F is then calculated by Eq. (2). [6]

$$E = RX \quad (2)$$

Where, E is the total domestic direct and indirect environmental impact vector;

R is the environmental intervention coefficient matrix, which is compiled to represent various releases (rows) per unit output from each sector (columns).

Then, the mathematical model of EIO-LCI can be written as:

$$E = RX = R(I - A)^{-1} F \quad (3)$$

A variety of environmental burdens might be calculated by EIO-LCI. Analyses have been performed with EIO-LCI, including resource requirements (electricity, natural gas, ores, and gasoline) and environmental impacts (toxic releases, solid waste, conventional air pollutant emissions, global warming potential and ozone-depleting substances) [8]. EIO-LCI using the published IOT has the advantage of tracing out full direct and indirect environmental impacts of outputs of industry sectors. However, it suffers from limitations of high levels of aggregation [9].

2.2. Integrated Hybrid Analysis

It is generally agreed that information from EIO accounts is less reliable than process-specific data due to temporal differences between input-output data and current process operation, aggregation, and import assumptions. The IOT is interconnected with the matrix representation of the physical product system at upstream and down-stream cut-offs where better data are not available. Suh and Huppes presented a hybrid model that integrates the computational structure of a P-LCI with an EIO-LCI within a consistent mathematical framework throughout the whole life-cycle of a product [4]. The mathematical model is as follows:

$$E = RX = RA_{int}^{-1}F = R \begin{bmatrix} A^* & -C^d \\ -C^u & I - A \end{bmatrix}^{-1} F \quad (4)$$

Where, matrix E is the environmental impact vector;
 R is the environmental intervention coefficient matrix;
 F represents a given exogenous demand;

Matrix A^* is the commodity-by-commodity input-output technology coefficient matrix. All life cycle stages, including material production, manufacturing, use and end-of-disposal, can be expressed by the technology coefficient matrix A^* , and A^* is expressed in various physical units per unit operation time for each process [4];

Matrix C^u represents upstream cut-off flows to the P-LCI system, linked with relevant sectors in IO table; it is evaluated in monetary units per unit operation time for each process;

Matrix C^d represents downstream cut-off flows to the IO system from the P-LCI system, C^d is evaluated in various physical units per unit of output for each input-output commodity in monetary terms [6];

Matrix A is the same as in Eq. (1), represents the direct requirements of the intersectoral relationships.

Using the IH-LCI model, detailed unit process level information is fully incorporated into the input-output model, which in turn represents the surrounding economy that embeds the process-based system. IH-LCI enables to give the total amount of environmental intervention resulting from the interaction between the functional flow-based system and the commodity-based system in both directions, in one consistent mathematical structure. [6]

3 Case Study

3.1. Goal and Scope Definition

The function unit in this study is defined as one STR series WD 615 diesel engine, used for five years (approximately 300000km of mileage), IH-LCI is conducted to investigate the quantitative assessment of energy consumption and environmental impacts of the diesel engine. The LCA is performed according to ISO 14040 [10]. The major technical parameters and materials of the engine are shown in Table 2.

The system boundary of this integrated hybrid LCA is shown in Fig. 2. The P-LCI model was applied within the dotted line and the EIO-LCI model was applied outside the boundary. The matrix A_{int} is obtained by integrating the P-LCI and the input-output structures.

Table 2. Major technical parameters of the diesel engine [11]

Parameters	Amounts	Unit
Weight	850	kg
Volume	9726	mL
Rated Power	213	kW
Rated Speed	2200	r/min
Torsion	1160	N.m

Table 2. Con.

Materials	Mass (kg)	Price (Yuan) [12]
Steel	188.19	812.2
Cast iron	578.83	1447.08
Aluminum & Alloy	72.82	1229.71
Rubber	5.44	92.7

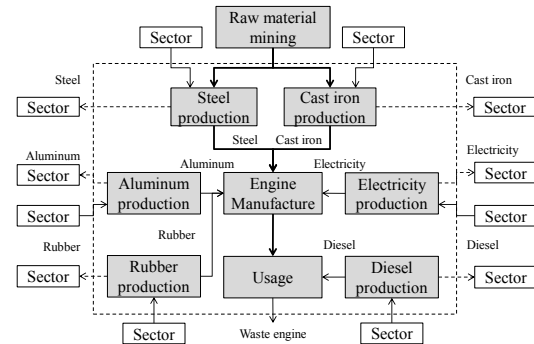


Fig. 2. The system boundary of the integrated hybrid LCA

3.2. Life Cycle Inventory Analysis

3.2.1. Data resources and calculation methods

Four submatrices $A_{8 \times 8}^*$, $C_{8 \times 26}^d$, $C_{26 \times 8}^u$, and $A_{26 \times 26}$ are synthesized into the matrix $A_{int(34 \times 34)}$. The data resources and calculation methods of the elements in these submatrices as well as an environmental intervention coefficient matrix $R_{6 \times 34}$ are shown in Table 3.

Table 3. The data resources and calculation methods of the model

Matrix	Data resource and calculation methods
$A_{8 \times 8}^*$	Industrial survey shown in Table 2; The coefficients are shown in Appendix A.
$C_{26 \times 8}^u$ & $C_{8 \times 26}^d$	The data in matrix $C_{26 \times 8}^u$ and $C_{8 \times 26}^d$ should be obtained from the cost sheet and distribution flows of the product, respectively. But those information are difficult to acquired, substitution and deductive method is conducted in this study: Electricity and the diesel consumption of each economic sector are obtained from the China energy statistical yearbook, 2008. [13]; Products and production processes are substituted by the corresponding sectors in IOT 2007, China [14] and the national economy industry classification and code [15]; Eight production processes in matrix $C_{26 \times 8}^u$ and six products in matrix $C_{8 \times 26}^d$ are substituted by the corresponding sectors in Appendix B.
$A_{26 \times 26}$	IOT 2007, China [14]
$R_{6 \times 34}$	China Statistical Yearbook on Environment 2008[16]; Reference[17]; CLCD

3.2.2. Results

In this study, the exogenous demand is defined as: $F = (0, 0, 0, 0, 0, 1, 0, \dots, 0)^T_{34 \times 1}$. The energy requirements and air pollutions of the engine's entire life cycle (not including the recycling) are calculated from Eq. (4). The result is shown in APP.C.

3.3. Interpretation

3.3.1. Inventory comparison

In P-LCI, each process is represented as a ratio between the number of inputs and outputs. Using plain algebra, the amount of commodities fulfilling a certain functional unit is obtained. Compared with P-LCI, IH-LCI has a clear advantage in terms of the quality of the result, especially in terms of system completeness. The comparison of energy requirements and air pollutants of a diesel engine is shown in Table 4 (not including recycling).

Table 4. Comparison of energy requirements and air pollutants of an engine

Environmental Impact	Items	IH-LCI (kg)	P-LCI[11] (kg)
Energy	ce	624843.92	116759.83
	CO ₂	522882.57	230054.77
	SO ₂	2098.29	189.46
Air pollutants	N ₂ O	1430.64	639.40
	CH ₄	4484.53	1324.17
	Dust	2574.76	326.33

Fig. 3, obtained from the data in Table 4, shows that the result achieved by IH-LCI is much higher than that of P-LCI, basically because the system boundary of P-LCI is defined subjectively and it is incompletely compared to that of IH-LCI. Consequently, the truncation error is unavoidable; instead, IH-LCI has a complete system boundary, which considers the environmental impact of P-LCI, upstream, and downstream sectors.

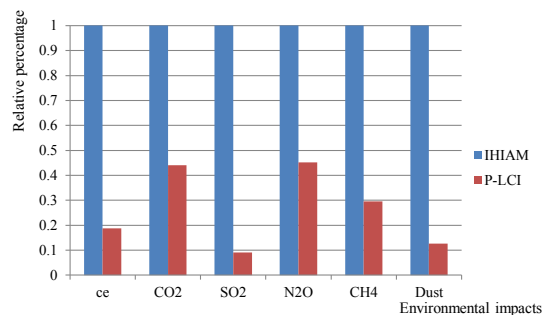


Fig. 3. Relative percentage of environmental impact of IH-LCI and P-LCI

3.3.2. Uncertainty analysis

The quality of the data obtained from different recourses needs to be checked by uncertainty analysis. This section evaluates the data uncertainty with Monte Carlo Simulation

Method (MCSM). Five data quality indicators (DQI) are considered including technical, time, and geographical representativeness as well as the data types [18]. Uncertainty of the original data U_0 can be calculated from Eq. (5):

$$U_0 = \sqrt{\sum_{i=1}^5 U_i^2} \quad (5)$$

Where, $i=1\sim5$, U_1 is source reliability, U_2 is sample integrity, and U_3, U_4, U_5 are technical, time and geographical representativeness, respectively. The data quality is scored by a spectrum matrix [19].

Take CO₂ as an example. The data resource of P-LCI is analyzed by mass / energy flows and the DQI score can be defined as (2, 2, 1, 1, 1) based on the spectrum matrix. The uncertainty U_0 (P-LCI) is:

$$U_{0-P-LCI} = \sqrt{\sum_{i=1}^5 U_i^2} = \sqrt{0.025^2 + 0.01^2 + 0^2 + 0^2 + 0^2} = 0.0269 \quad (6)$$

The data recourse of IH-LCI is partly cited from IOT 2007 and China Statistical Yearbook on Environment 2008. The calculated DQI score is (2, 1, 4, 2, 2) and uncertainty U_0 (IH-LCI) is 0.2022.

U_0 is defined as the Relative Standard Deviation (RSD) of Gaussian distribution. Crystal Ball®2000 Professional Edition is applied to conduct MCSM.

Figs. 4&5 illustrate the frequency view of MCSM of the CO₂ LCI results (10000 repetitions, 95% confidence interval).

The RSD and limits of CO₂ LCI result is shown in Table 5. The uncertainty of the final LCI result U_f can be presented by the final LCI results RSD.

Table 5 shows that uncertainty of CO₂ LCI results, achieved by P-LCI, is lower than that of IH-LCI. The reason is that P-LCI shares the up-to-date information and newer technologies, which shows a more accurate technical, time, and geographical representativeness of raw materials production as well as engine manufacturing.

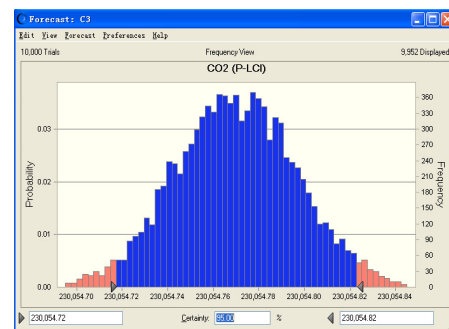


Fig. 4. Monte Carlo Simulation of the CO₂ P-LCI results

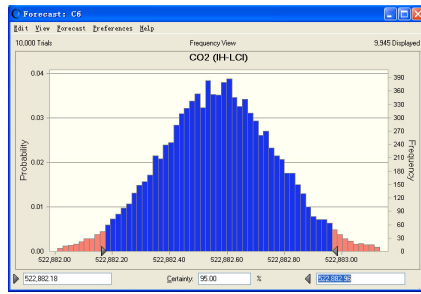


Fig. 5. Monte Carlo Simulation of the CO₂ IH-LCI results

Table 5. Uncertainty check of the CO₂ LCI result

Data sources		P-LCI	IH-LCI
CO ₂ /kg	Mean	230054.77	522882.57
	RSD	0.03	0.20
	Limits	[-0.109, +0.100]	[-0.789, +0.750%]

4 Conclusions

This paper uses IH-LCI to evaluate the energy consumptions and environmental emissions of an engine. APP.C shows that during the entire life cycle of an engine, the greatest environmental impacts are generated in the operation period followed by production of materials such as cast iron, aluminum, electricity, diesel, etc. Replacing the materials with large energy consumption and emissions under the precondition of ensuring the performance is an available

proposal to make the engine “greener”. And improving the fuel efficiency and apply the alternative fuel, such as hydrogen and methyl alcohol, to reduce the environmental impacts in the operation period.

The result achieved by IH-LCI is much higher than that of P-LCI because IH-LCI has a complete system boundary. It not only considers the environmental impact of P-LCI, but the environmental impact of the relative upstream and downstream sectors as well. With a more accurate technical, time and geographical representativeness of raw materials production and engine manufacturing, the uncertainty of LCI results achieved by P-LCI becomes lower than that of IH-LCI.

As an existing IOT cannot present the direct information for matrix C^u and C^d , substitution and deductive method is conducted and the boundary between PLCI and IH-LCI is delimited subjectively in this study. In order to achieve a more accurate result, the research should focus on reasonable system boundary delimitation and the real data mining for upstream cut-off flows to the target LCA system and from the target LCA system to downstream cut-off flows.

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Appendices

Appendix A. The coefficients of the technical matrix $A_{8 \times 8}^*$

	Production of steel	Production of cast iron	Production of aluminum	Production of rubber	Production of electricity	Manufacturing of engine	Production of diesel	Use of engine
Steel(kg)	1	0	0	0	0	-188.19	0	0
Cast iron(kg)	0	1	0	0	0	-578.83	0	0
Al & Alloy(kg)	0	0	1	0	0	-72.82	0	
Rubber(kg)	0	0	0	1	0	-5.44	0	
Electricity (kW.h)	0	0	0	0	1	-2296.21	0	0
Engine	0	0	0	0	0	1	0	-1
Diesel(kg)	0	0	0	0	0	0	1	-63750
Wasted engine	0	0	0	0	0	0	0	1

Appendix B. Processes / products and the corresponding sectors in matrix $C_{26 \times 8}^u$ and $C_{8 \times 26}^d$

Sectors	$C_{26 \times 8}^u$	$C_{8 \times 26}^d$
	Process	Product
Steel making industry	Production of steel	Steel
Iron making industry	Production of cast iron	Cast iron
Non-ferrous metal smelting and metal manufacturing industry	Production of aluminium	Al & Alloy
Rubber manufacturing industry	Production of rubber	Rubber
Production and supply of electric power and heat power	Production of electricity	/
Manufacture of automobile	Manufacturing of engine	Engine
Processing of Petroleum, Coking, Processing of Nuclear Fuel	Production of diesel	/
Transport industry	Use of engine	Wasted engine

Appendix C. Energy requirements and air pollutions of an engine

	Energy	Air pollutions/kg				
	/kg ce	CO ₂	SO ₂	N ₂ O	CH ₄	Dust
1.Cast iron	3476.37	8816.79	18.74	9.30	20.55	53.04
2.Aluminum	6891.94	15721.46	54.19	38.91	44.46	30.77
3.Electricity	57951.64	125464.90	428.46	349.77	363.57	1640.78
4.Diesel	150921.70	31625.98	223.06	52.68	1728.70	176.48
5.Wasted engine	304328.00	330925.10	256.97	930.23	1927.86	249.55
6.Mining and Washing of Coal	5330.48	67.42	13.03	0.35	303.05	6.84
7.Smelting and Pressing of Metals	22014.53	413.17	25.74	0.44	0.07	31.40
8.Production and supply of electric power and heat power	13770.84	37.27	855.06	0.12	4.93	221.67
Else	60158.42	9810.48	223.04	48.84	91.21	164.23
Total	624843.92	522882.57	2098.29	1430.64	4484.53	2574.76

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